ICESat-2, SkySat, WorldView and Sentinel: Automated Extraction of High-Resolution Spatial Information for Investigation of Surging and Fast-Moving Glaciers

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Abstract

Glacial acceleration is the largest source of uncertainty in sea-level-rise assessment, according to the Intergovernmental Panel on Climate Change. Of the different types of glacial acceleration, surging is the least understood. In this paper, we demonstrate how a combination of automated algorithms dedicated to analysis of two entirely different observation types - satellite altimetry from NASA's ICESat-2 and satellite imagery from Planet SkySat - can aid in advancing glaciology, utilizing state-of-the art remote sensing /Earth observation technology. NASA's Ice, Cloud and land Elevation Satellite ICESat-2, launched 15~September~2018, carries the first space-borne multi-beam micro-pulse photon counting laser altimeter system, the Advanced Topographic Laser Altimeter System (ATLAS). ATLAS observations are collected in three pairs of weak and strong beams with 0.7m nominal along-track spacing (under clear-sky conditions). The recording of the observations as a photon-point cloud requires a dedicated algorithm for identification of signal photons and determination of surface heights. As a solution, we developed the density-dimension algorithm for ice surfaces, the DDA-ice. ATLAS data analyzed with the DDA-ice allow determination of heights over heavily crevassed ice surfaces, which are characteristics of accelerating glaciers. The study presented here builds on a special multi-component data set, obtained through synoptic observations of an Arctic glacier system during surge (Negribreen, Svalbard): Airborne altimeter and image data collected during our ICESat-2 validation campaign, and SkySat image data from a special acquisition collected as part of NASA's Commercial Smallsat Data Acquisitions Pilot program. These are complemented by WorldView (Maxar) and ESA Sentinel-1 data. With a spatial resolution of 0.7-0.86m, SkySat data and WorldView lend themselves to automated classification of crevasse types. Altogether, we obtain a characterization in 3 dimensions that allows discrimination of ice-surface types from surging glaciers (Negribreen) and continuously fast-moving and accelerating glaciers (Jakobshavn Isbrae) based on morphological characteristics.

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AGU Fall Meeting 2020

Objectives

(1) Glacial Acceleration as the Largest Source of Uncertainty in Sea-Level-Rise Assessment
   (a) Surge Glaciers: Surge of Negribreen, Svalbard, and Potential Disintegration of the Negribreen Glacier System
   (b) Fast-moving glaciers: Jakobhavn Isbræ, Greenland

(2) Assessment of SmallSat Image Data for Cryospheric Sciences (CSDAP)
   (a) WorldView 1-3 (Maxar, formerly DigitalGlobe)
   (b) Planet PlanetScope, SkySat, RapidEye

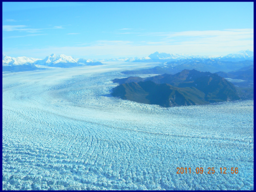
(3) ICESat-2 Airborne Validation Campaigns 2018 and 2019
   (a) Assessment of ICESat-2 ATLAS measurement capability over complex ice surfaces: crevasses, fractures, rifts, water on ice, firn, snow, bare ice
   (b) Evaluation of ICESat-2 Height Determination over Crevassed and Other Complex Glaciated Terrain: The Density Dimension Algorithm for Ice Surfaces — DDA-ice
   (c) Crevasse types of Negribreen and Jakobshavn Isbræ

(4) Surface Roughness Characterization and Crevasse Classification: A Cyberinfrastructure to aid Glaciological Research
   (a) Spatial Surface Roughness from Imagery
   (b) Crevasse Classification for Negribreen during Surge from WorldView and SkySat Imagery

(5) Growing a Community of Users: Development and Sharing of two Cyberinfrastructures

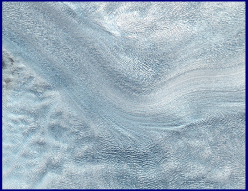
Acknowledgements: Work on SmallSat assessment supported by NASA Commercial SmallSat Data Acquisition Program (CSDAP), work on ICESat-2 algorithm development, validation and science applications supported by NASA Earth Sciences and the ICESat-2 Project; research on Negribreen Surge also supported by NSF Arctic Natural Sciences. Research on image classification supported by NASA and NSF CSSI and ANS. A contribution to Svalbard Integrated Earth Observing System (SIOS), registered as Research in Svalbard Project RIS-10827 "Negribreen Surge" (2017-2019). Thanks due to colleagues at the ICESat-2 Project, ASAS and the ST, especially to Tom Neumann, David Hancock and Kaitlin Harbeck, to Planet for SkySat acquisition, to colleagues and staff at SIOS, NPI, UNIS and Airlift and captain and crew of R/V Lance, especially to our pilots and technicians Anders Bjørghum, Gunnar Nordahl, Tor Andre Vaksdal, Harald Sandal and Gustav Svanström (Airlift), to Inger Jennings and Heikki Lihavainen (SIOS), to Jack Kohler, Havard Hansen, Harvey Goodwin, Geir Ove Aspnes, Jørn Dybdahl (NPI) and Chris Borstad (UNIS, now University of Montana), Kristin Woxholth, Longyearbyen, to Annie Zaino, Joe Pettit, Spencer Niebuhr (UNAVCO Boulder) and to Geomath team members Sam Bennetts, Connor Myers and Jacob Hans.

Surface Roughness and Crevasses as Indicators of Glacial Acceleration

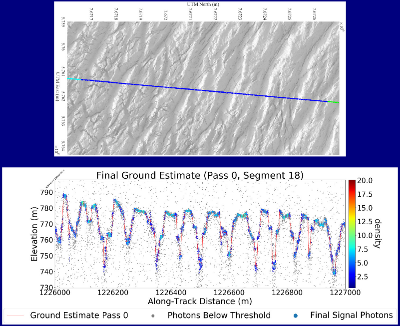


Bering Glacier, Alaska, Surge 2011

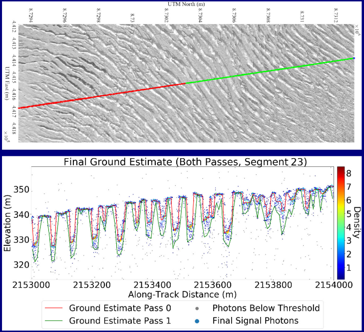
Negribreen, Svalbard, Surge 7/2017



Jakobshavn Isbræ [Sentinel-2]



Jakobshavn crevasses [DDA-ice-1]



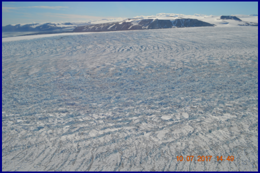
Negribreen surge crevasses w water [DDA-ice-2]

SkySat validation of DDA-ice algorithm applied to ICESat-2 ATLAS data (Herzfeld et al., subm and in prep. 2020)

Negribreen during surge (2017-2019): An ideal test situation for evaluation of height determination over crevassed and other complex ice surfaces

Negribreen Surge 7/2017

Negribreen Surge 7/2017



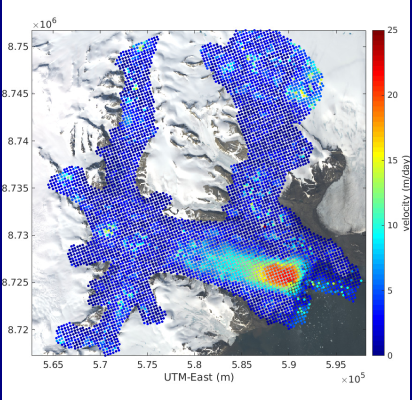
Negribreen Surge 7/2017

Negribreen Surge 7/2017

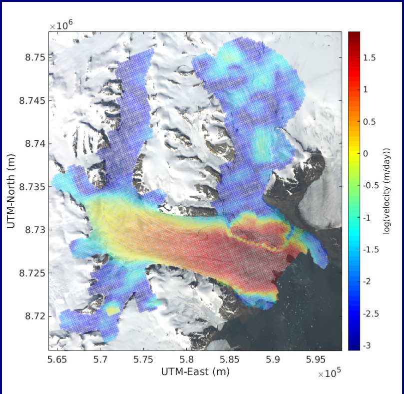
Ordonannsbreen-Negribreen 2019

Negribreen Surge 8/2019

Negribreen Velocity Maps from Sentinel-1 SAR Data



(a) July 2017: Maximal velocities (≈22 m/day)



(b) May 2019: Surge expansion (log velos)

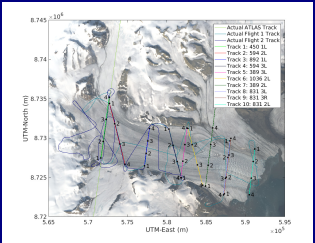
Resultant mass loss is on the order of 1% of annual global SLR (calculated for only 4 months during peak of surge in 2017)

Herzfeld, Trantow, Bennetts (in review)

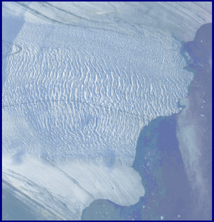
ICESat-2 Airborne Validation Campaign 2018-2019: NASA/SIOS

Objectives

- Underflights of future ICESat-2 tracks (July 2018)
- Underflights of near-time ICESat-2 tracks (August 2019)
- Optimization of airborne geolocation accuracy using RTK GPS
- Special Acquisition of PlanetLab SkySat Data
- Assessment of surface-height determination of ICESat-2 over crevassed and otherwise complex ice surfaces, using the DDA-ice-1 and DDA-ice-2 for analysis



Flight 1, 2019-Aug-12; Flight 2: 2019-Aug-13
Landsat-8, 2019-08-05



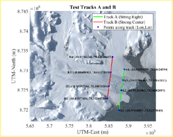
SkySat Image 2019-Aug-18

Field Team 2019

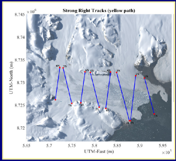
ICESat-2 Airborne Validation Campaigns 2018-2019: NASA/SIOS

Combining observation of the surge with airborne evaluation of ICESat-2 data:
A contribution to Svalbard Integrated Arctic Earth Observing System (SIOS),
ICESat-2 Evaluation and Assessment of RTK GPS (UNAVCO)

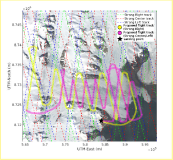
- Underflights of future ICESat-2 tracks (July 2018)
- Optimization of airborne geolocation accuracy using RTK GPS



Experiment 1



Experiment 2


Planned flight paths

NASA/SIOS 7/2018

Experiment Setup:

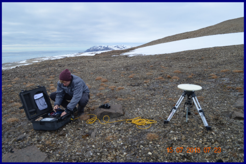
(1) Laser altimetry (ULS (Lasertech), CU Geomath Integration)

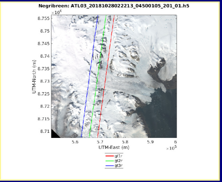
(2) Time-laps imagery (Go-Pro Hero5)

(3) IMU Data (Attitude Correction)

(4) On-board Kinematic GPS

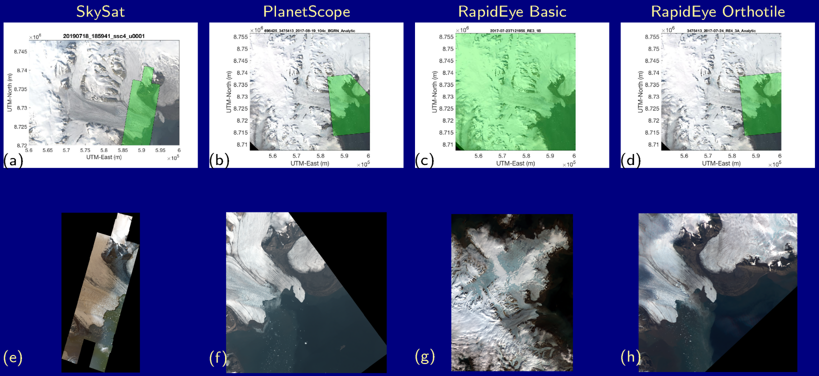
(5) Experiments with RTK


GPS Base Station 7/2018



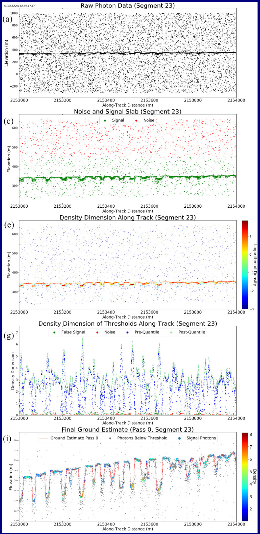
ICESat-2 data selected (gt1r) (v201, v205)

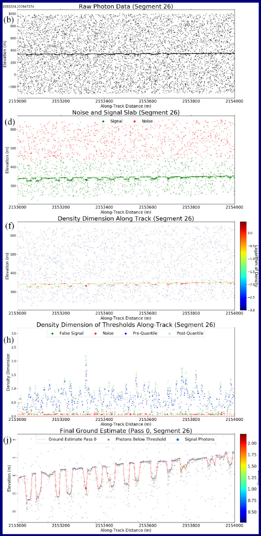
Planet Satellite Image Types and Coverage: Negribreen, Svalbard (2017-2019)

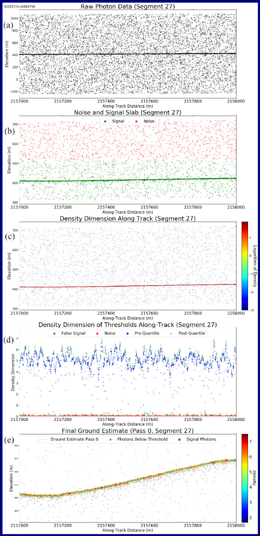


Surge of an Arctic Glacier (Negribreen, Svalbard) in the view of several SmallSat image types: Comparison of coverage and resolution. (a)-(d) Coverage, (e)-(h) Imagery. (a), (e) Planet Skysat Collect (20190718_185941_ssc4_u0001). (b), (f) PlanetScope (696425_3475413_2017-08-19_104c_BGRN_Analytic), (c), (g) RapidEye Basic (2017-07-23T121955_RE3_1B), (d), (h) RapidEye Orthotile (3475413_2017-07-24_RE4_3A_Analytic). Background in (a)-(d) Landsat 8 from 2017-07-07.

The Density-Dimension Algorithm for ICESat-2 Ice-Surface Data (DDA-ice)





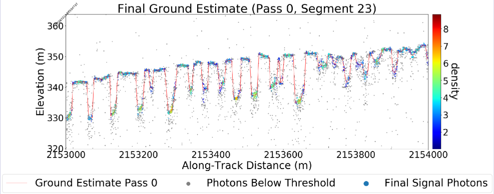


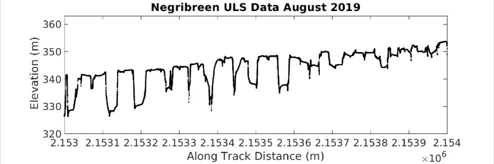
strong beam
Herzfeld et al., 2017; Herzfeld et al. in press

weak beam

uncrevassed ice

ICESat-2 DDA-ice Surface Heights and Surface Roughness Compared with Airborne Altimeter (ULS) and SkySat Data



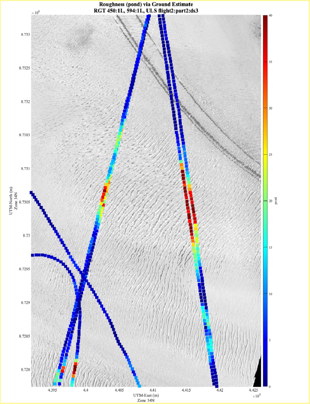


	Mean Crevasse Spacing (m)	Maximum Crevasse Depth (m)	Mean Crevasse Depth (m) ($> 5m$)
DDA-ice	52.12	16.01	10.95
ULS	58.82	13.96	10.18

Table 3: Crevasse spacing and depths for Negribreen evaluation profile "segment 23 (RGT594) 2019-08-05". Comparison of results from ULS airborne laser altimeter data and DDA-ice applied to ICESat-2 ATLAS data ATL03_20190805232841_05940403_002_01.h5.

Note that ULS uses 905 nm.

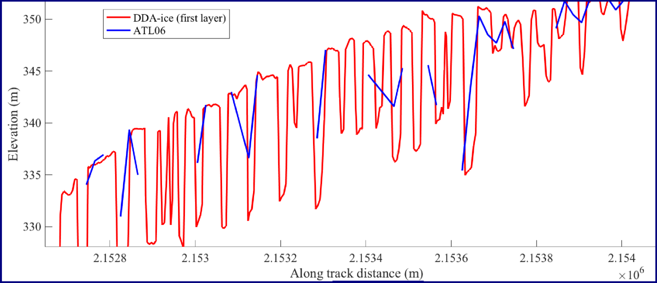
Results from August 2019 Validation Campaign.



Surface roughness from ICESat-2 DDA-ice results, over SkySat imagery shows roughness aligns with crevasse fields.
SkySat Image [20190818_150858_ssc9_u0002_panchromatic_dn.tif]
SkySat ssc9 data have 0.72 m pixel size.

From Herzfeld et al., 2020 (in review)

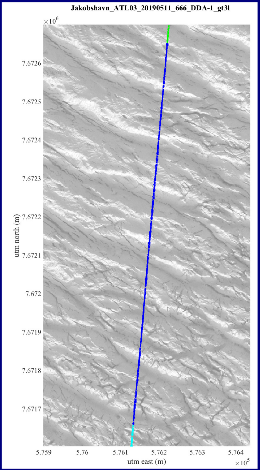
Information gain compared to ATL06



Comparison of results from DDA-Ice algorithm and ATL06 [ATL06_20190805232841_05940403_002_01.h5, ATL03_20190805232841_05940403_002_01.h5] [RGT 594 gt1l 2019-08-05] strong beam. Negribreen crevasses.

Comparison with airborne data and SkySat data supports assessment of information gain from DDA-ice results over crevassed regions.

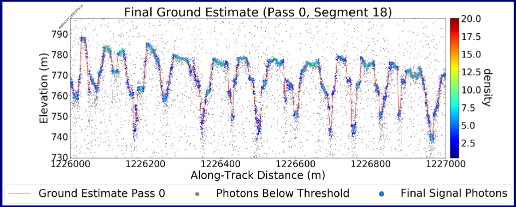
Jakobshavn Isbræ (Ilulissat Ice Stream) Multi-generational crevasses measured with ICESat-2 and validated using PlanetLab SkySat data   Ute Herzfeld +group



Multi-generational crevasse provinces

in Jakobshavn Isbræ

(1) PlanetLab SkySat imagery from special acquisition 24-October-2019
(2) ICESat-2 data from 11-May-2019 (v002)

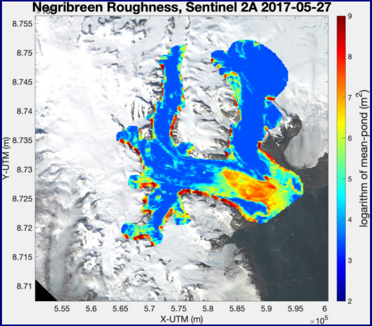


ICESat-2 surface heights, determined using the DDA-ice

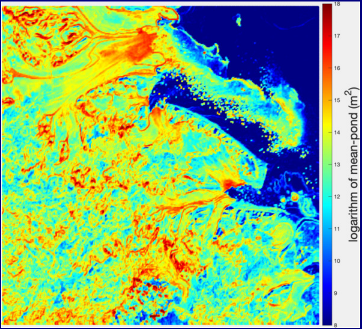
- ICESat-2 data have 0.7m along-track nominal spacing, SkySat has 0.7m pixel resolution.
- We developed a visualizing tools that allows to match ICESat-2 tracks and SkySat data and zoom into every detail (top SkySat corresponds to left in ICESat-2 fig).
- This allows to see a one-2-one match of every single crevasse and crevasse detail.
- ATLAS penetrates into very thin crevasses at the bottom of crevasse groups.
- DDA-ice measures depths to 45m, with an average of 35-40m, and resolves crevasse morphology.

After Herzfeld et al. (in press 2020)

Negribreen Ice-Surface Roughness from ESA Copernicus Sentinel-2 and Planet RapidEye Image Data



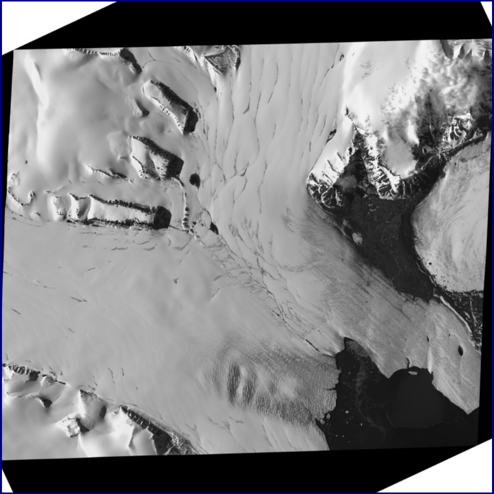
Sentinel-2. 10 m pixels.
Roughness map at 200 m resolution
Result: Map shows surge expansion.



RapidEye. 6.5 m pixels.
Roughness map at 130 m resolution
Result: Map shows features of surging glacier and mass loss through calving.

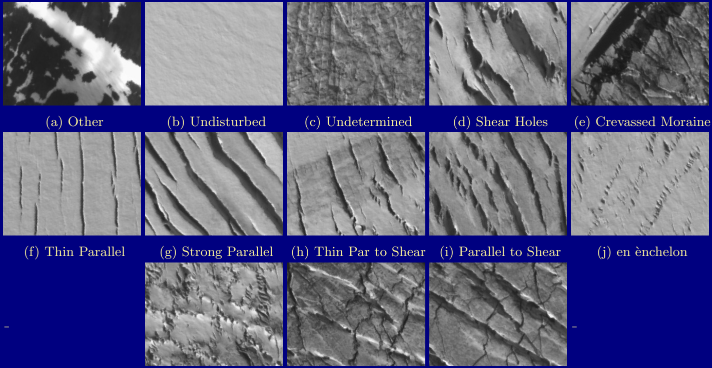
from Herzfeld et al., in prep.

Negribreen in June 2016 from WorldView Data



WV02_20160625170309_1030010059AA3500_16JUN25170309-P1BS-500807681050_01_P004_u16ns3413-BROWSE.png

Negribreen — 13 crevasse classes



(a) Other (b) Undisturbed (c) Undetermined (d) Shear Holes (e) Crevassed Moraine

(f) Thin Parallel (g) Strong Parallel (h) Thin Par to Shear (i) Parallel to Shear (j) en ènchelon

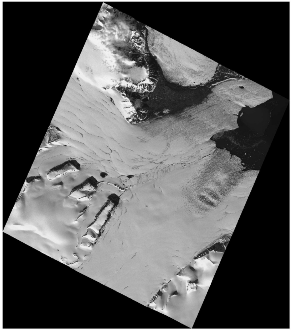
(k) Subordinate Shear (l) Multigenerational (m) Multidirectional

13 Crevasse classes derived from WV02_20160625170309 and used for connectionist-geostatistical classification

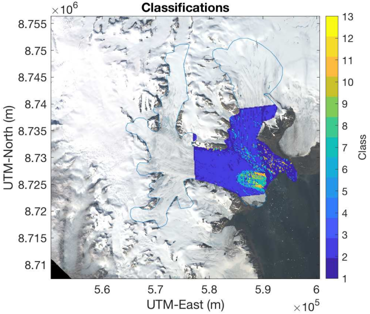
from Herzfeld et al. (in prep. 2020)

Negribreen — Time series of crevasse provinces during surge

2016-June-25



(a) WV02_20160625170309 original image



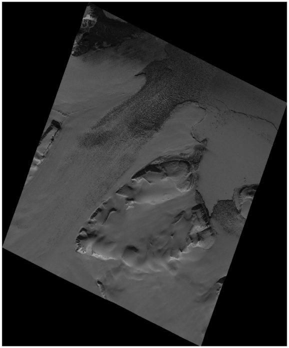
(b) WV02_20160625170309 classification

Result of connectionist-geostatistical classification based on 13 crevasse classes

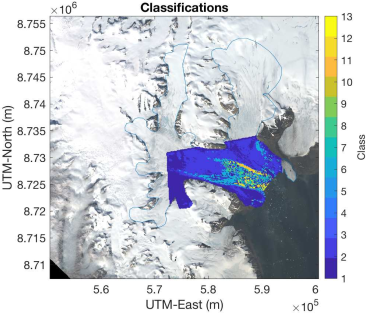
from Herzfeld et al. (in prep. 2020)

Negribreen — Time series of crevasse provinces during surge

2017-May-30



(c) WV01_20170530144716 original image



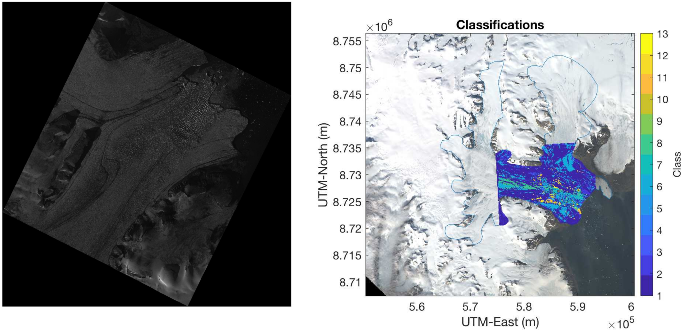
(d) WV01_20170530144716 classification

Result of connectionist-geostatistical classification based on 13 crevasse classes

from Herzfeld et al. (in prep. 2020)

Negribreen — Time series of crevasse provinces during surge

2017-July-7



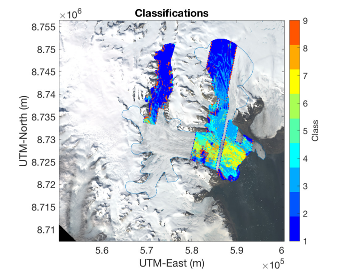
(e) WV02_20170731184242 original image

(f) WV02_20170731184242 classification

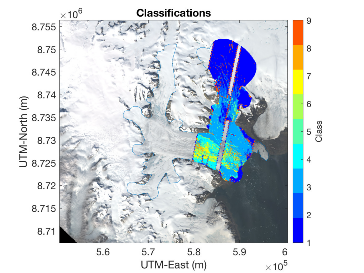
Result of connectionist-geostatistical classification based on 13 crevasse classes

from Herzfeld et al. (in prep. 2020)

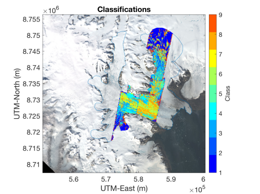
Connectionist-geostatistical classification of ice surfaces from Planet SkySat data



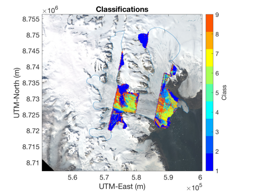
20190818 - ssc 9 (0.72m)



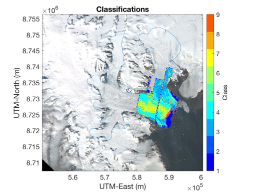
20190922 - ssc 1 (0.86m)



20190803 - ssc2 (0.86m), 20190805 ssc11 (0.72m)



20190717 (ssc3) and 20190718 - ssc4 (both 0.72m)



20190725 - ssc8 (0.72m)

Growing a Community of Users: Development and Sharing of two Cyberinfrastructures (Open Source/Open Science)

(1) The Density-Dimension Algorithm family for ICESat-2 laser altimetry: Surface heights, clouds, aerosols [NASA ICESat-2 Science Team Project]

(2) The Connectionist-Geostatistical Classification framework for satellite image analysis [NSF OAC Project]

Future: Integration of (1) and (2) for combined analysis of altimetry and satellite imagery as a means to advance (cryospheric) sciences

Open Source — Open Science

- Growing a community of users
- Early adopters of our algorithm family
- github, doxygen and all that
- Experiments on the cloud
- In-person workshops and online-courses
- Open-access algorithm publications and online documentation
- Generalizations: Other disciplines and applications/ applied sciences

Data Access and References

Data and Report Access

(1) Our 2019 Commercial SmallSat Data Acquisition Program (CSDAP) link: https://cdn.earthdata.nasa.gov/conduit/upload/14158/CSDAP-Pilot-Herzfeld.pdf

(2) ICESat-2 data products are available under https://earthdata.nasa.gov/.

References

(1) HERZFELD, UTE C. , THOMAS TRANTOW, DAVID HARDING and PHILIP DABNEY (2017), Surface-Height Determination of Crevassed Glaciers — Mathematical Principles of an Auto-Adaptive Density-Dimension Algorithm and Validation Using ICESat-2 Simulator (SIMPL) Data, IEEE Transactions in Geoscience and Remote Sensing, volume 55, number 4, April 2017, p. 1874-1896, doi:10.1109/TGRS.2016.2617323

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